REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
08-11-2006

2. REPORT TYPE
Conference Paper PREPRINT

3. DATES COVERED *(From - To)*
2001 - 2006

4. TITLE AND SUBTITLE
High Capacity Two-Stage Pulse Tube (PREPRINT)

5a. CONTRACT NUMBER
F29601-01-C-0226

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63871C

6. AUTHOR(S)
C. Jaco, T. Nguyen, D. Harvey, and E. Tward

5d. PROJECT NUMBER
2402

5e. TASK NUMBER
CC

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Northrop Grumman Space Technology
One Space Park
Redondo Beach, CA 90278

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Space Vehicles
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/VSSE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-VS-PS-TP-2007-1010

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited. (Clearance #VS06-0810)

13. SUPPLEMENTARY NOTES
Submitted to the 2007 Cryogenic Engineering Conference and International Cryogenic Material Conferences, TBD, Chattanooga, TN

Government Purpose Rights

14. ABSTRACT
The High Capacity Cryocooler (HCC) provides large capacity cooling at both 35 K and 85 K for space applications in which focal planes and optics require cooling. The compressor is scaled from the High Energy Cryocooler (HEC) compressor and is capable of using input powers up to 700 W. The two linear pulse tube cold heads are integrated with the compressor into an integral cryocooler. A thermal strap between the cold heads improves efficiency and can be positioned to provide cooling for a wide range of applied loads. The cooler has undergone acceptance testing that includes thermal performance mapping over a range of reject temperatures and power levels and launch vibration testing. In addition to the acceptance testing, self induced vibration measurements were made over a range of reject temperatures and power levels.

15. SUBJECT TERMS
HCC, High Capacity Cryocooler, Cryocooler, Cooling, Space Applications, Focal Planes, Optics, HEC, High Energy Cryocooler

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unlimited	11	Lt William Scheirer
					19b. TELEPHONE NUMBER *(include area code)* 505-846-9630

HIGH CAPACITY TWO-STAGE PULSE TUBE

C. Jaco, T. Nguyen, D. Harvey, and E. Tward

Northrop Grumman Space Technology
Redondo Beach, CA, USA

ABSTRACT

The High Capacity Cryocooler (HCC) provides large capacity cooling at both 35 K and 85 K for space applications in which focal planes and optics require cooling. The compressor is scaled from the High Energy Cryocooler (HEC) compressor and is capable of using input powers up to 700 W. The two linear pulse tube cold heads are integrated with the compressor into an integral cryocooler. A thermal strap between the cold heads improves efficiency and can be positioned to provide cooling for a wide range of applied loads. The cooler has undergone acceptance testing that includes thermal performance mapping over a range of reject temperatures and power levels and launch vibration testing. In addition to the acceptance testing, self induced vibration measurements were made over a range of reject temperatures and power levels.

INTRODUCTION

The High Capacity Cryocooler (HCC) as shown in Figure 1 is a two-stage pulse tube cooler developed to provide a long life, low mass, higher efficiency space cryocooler on missions such as Space Tracking and Surveillance System. The cooler has an objective to extend the performance of proven, high efficiency, lightweight pulse tube cooler technology to larger capacity, lower temperature and staged operation.

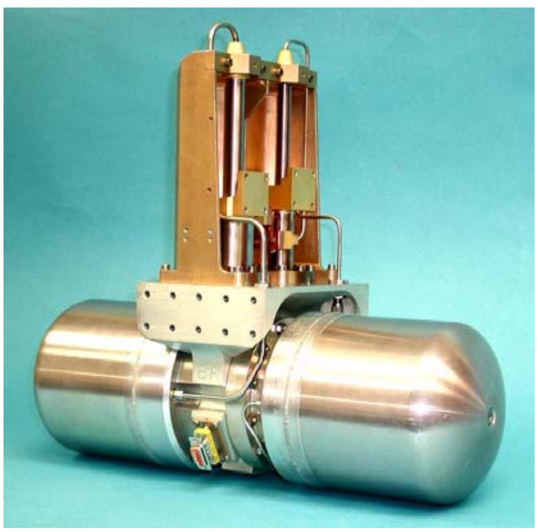

FIGURE 1. Two-Stage High Capacity Cryocooler

Because of its high efficiency and very low mass/unit capacity, the HCC can be applied to simultaneously cool long wave infrared (LWIR) focal planes (as low as 30 K) and optics (60 K to 150 K). Although the HCC was designed to cool 2 W @ 35 K and 16.5 W @ 85 K, the variable position strap between the coldheads allows for a broad range of applied loads and temperatures. As delivered, the strap location provides cooling of 1.8 W @ 35 K and 19 W @ 85 K with an input power of 530 W, centerplate temperature of 300K and reject temperature of 285 K. The HCC achieves low input power and large cooling load because of the efficiency of its pulse tube cold heads and its efficient compressor. The low mass results from the use of the second-generation flexure compressor technology developed with Oxford University and productionized for Northrop Grumman by Hymatic Engineering [1].

CRYOCOOLER

The cooler characteristics are summarized in Table 1. The HCC two-stage cold heads are designed in an integral parallel configuration. In this design, the 1st and 2nd stage cold heads are mounted directly on the compressor center plate. The oscillating flow from the compressor is split into the two cold heads in proportion to their required thermal design performance. The parallel two-stage cold head configuration has the advantage that there is minimal interference in the thermal performance of the two stages, i.e., changes in cooling at one stage has a small effect on the other stage.

TABLE 1. Typical Cooler characteristics

Cooling load at 85 K	19.0 W
Cooling load at 35 K	1.8 W
Input power	530 W
Centerplate temperature	300 K
Maximum input power capability	700 W
Cooler mass	14.3 kg

The two-stage cold head is mounted onto a back-to-back compressor, designed to achieve both long lifetime and vibration balance. The flexure springs are very stiff in the direction perpendicular to the driven motion (much stiffer than gas or magnetic bearings) so that close tolerance gas gap seals can be maintained and wearing seals can be eliminated. The flexures themselves are designed for maximum stress levels well below the material endurance limits. Their reliability is validated in the compressor since over 10^7 cycles are accumulated in 4 to 5 days with these compressors. The working fluid is dry helium with no lubricants. The drive is a direct voice coil motor similar to a loudspeaker drive, thereby eliminating linkages.

The cooler components are shown in Figure 2. The linear cold heads are attached to the centerplate and hermetically sealed with a metal C-ring. The cold heads containing the regenerators, cold blocks, pulse tubes and orifice blocks are mechanically supported against launch loads by a support structure. The two cold block interfaces are gold plated and located near the midpoint of the cold heads. The 35 K cold head is provided with redundant calibrated platinum resistance thermometers used for temperature control. The thermal strap between the 85 K cold block and the 35 K regenerator provide overall system power reduction. Centerplate temperature is measured using a thermistor bonded to the top of the centerplate between the coldheads. Also located on the centerplate

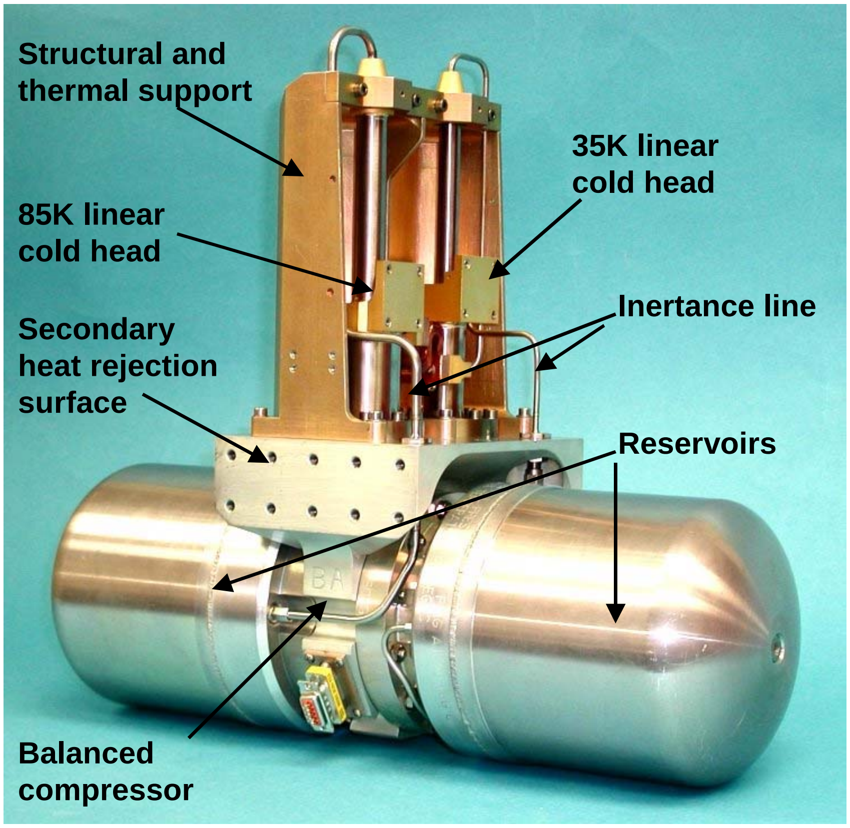

FIGURE 2. Cooler components

is an accelerometer that is used to sense cooler self-induced vibration. The accelerometer preamplifier, which is mounted on the centerplate, amplifies the accelerator signal for transmission to the control electronics. Here it is used as an error signal in a feedback loop to reduce the vibration to very low levels. The compressor end caps, which also enclose the reservoir, are hermetically sealed by metal C-rings. The centerplate incorporates simple and effective mechanical and thermal interfaces to payloads. The primary mechanical mounting interfaces of the compressor can adequately remove up to 400 W of heat by direct conductive heat transfer to the mount surface. For greater input powers to the 700 W limit, a secondary thermal interface is provided for extra heat removal capability.

After assembly, the bake out process performed on the cooler reduces volatile condensables and water in the machine to negligible levels. All Northrop Grumman coolers are hermetically metal sealed to have minimum detectable leakage rates of helium fluid. The processes have been verified by life tests of similar pulse tube coolers and in-flight history of the eleven other Northrop Grumman pulse tube units that are currently in orbit.

COOLER PERFORMANCE

Figure 3 shows a typical performance map of the two-stage cooler at fixed input power and reject temperature. Note that as the applied load on the higher temperature coldhead (stage 1) is reduced from the maximum value shown of 19 W to 0 W, the temperature of the lower temperature coldhead (stage 2) with constant load of 1.8 W is affected by only 2.5 K. Similarly when the load on the stage 1 is held fixed and the load on stage 2 is varied from 1.8 W to 0.4 W, the stage 1 temperature varies by less than 1.5 K. This implies that the thermal performance of each cold head is independent of the other. In a parallel

multistage configuration, there is little interference between the stages. This is very important in reducing risk for an immature payload design. Figure 4 shows a typical performance map of the HCC cooler as a function of the input power with a given strap location. As the input power is reduced, the cooling loads are reduced while maintaining the efficiency of the system. In these measurements the HCC cooler maintains its efficiency as the input power is reduced from 500W to 178W. The HCC cooler can be optimized at different first stage cooling temperatures. Table 2 summarizes the performance at two cooling loads at 35 K and different temperatures of the first stage.

The High Capacity Cryocooler has undergone acceptance test prior to its delivery to the Air Force. The complete suite of acceptance tests include thermal performance mapping over a wide range of reject temperatures and power levels, launch vibration testing and thermal vacuum tests. The engineering model cooler was tested under the random launch vibration conditions shown in Figure 5, that are acceptance levels. The overall random vibration level is 8.65 Grms. The cooler was also acceptance tested under different thermal conditions. The thermal cycle profile is shown in Figure 6a. Thermal cycle test data is shown in Figure 6b. Extensive thermal and dynamic analyses were conducted on the HCC. The results of the analyses are summarized in Table 3. Additionally, the self-induced vibration of the cooler was measured at various centerplate temperatures and input powers. The 500W/300K results are shown in Figures 7-9 for each of the three axes. The self induced vibration was measured with the cooler mounted inside a bell jar attached to a force plate with four force transducers. The fundamental and harmonics are labeled on the plots in order to distinguish them from the background noise of the vacuum pump and cooling water recirculator. The background noise disappears when the laboratory support systems are not operating, but the cooler operating time during test is then limited.

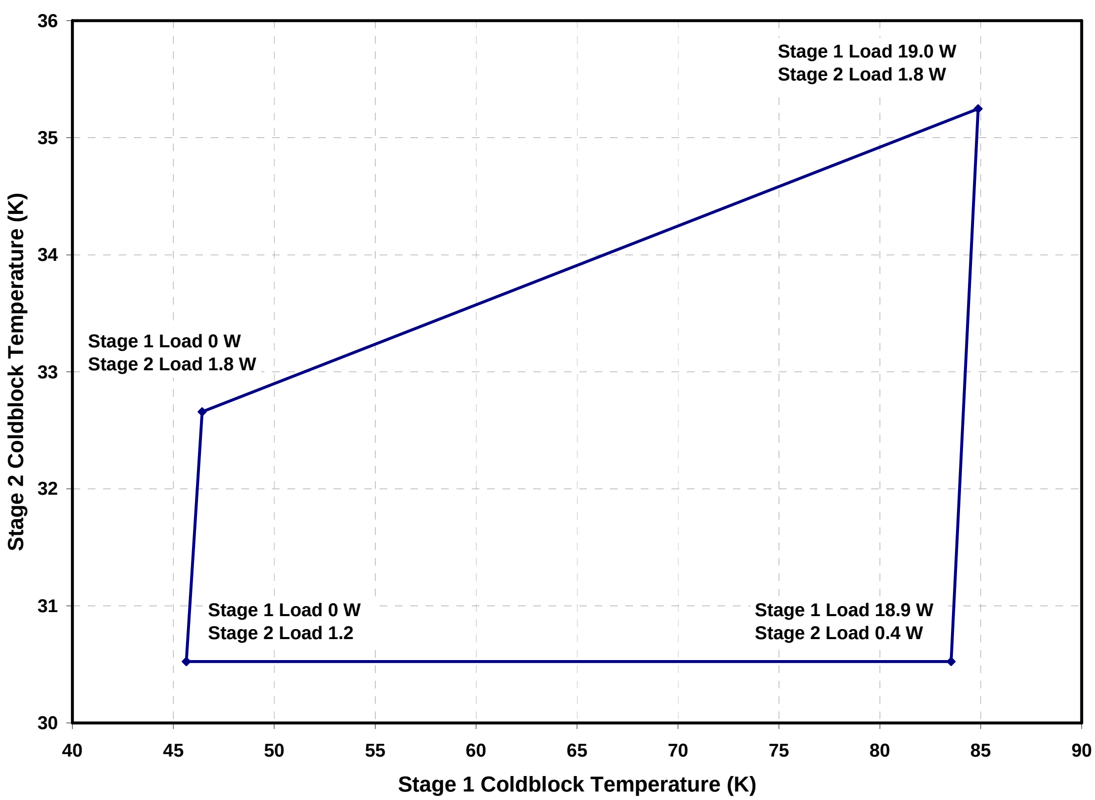

FIGURE 3. Two stage cold head performance map

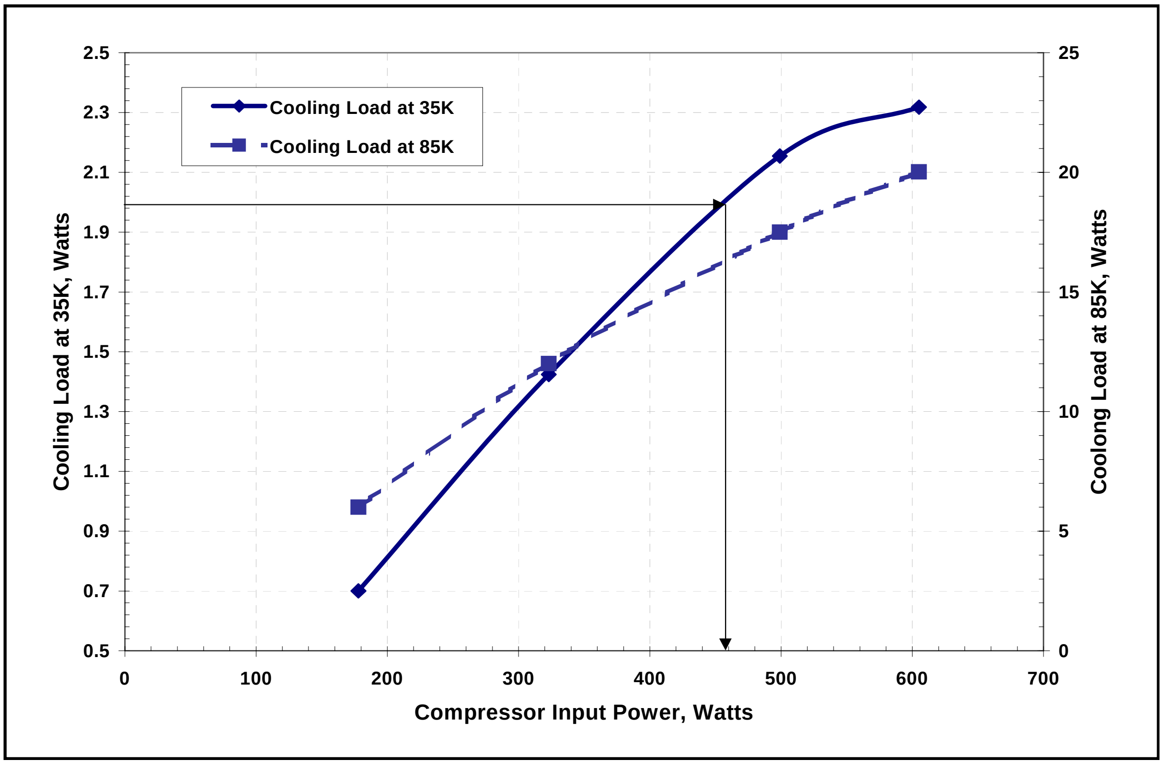

FIGURE 4. Two stage cold head performance as function of input power

TABLE 2. HCC performance at different temperatures of first stage

Stage 1 Temperature	Stage 1 Load	Stage 2 Temperature	Stage 2 Load	Input Power
85 K	16.8 W	35 K	2 W	501 W
111 K	12.55 W	35 K	0.7 W	209 W

TABLE 3. Thermal, stress and dynamic margin for qualification levels

Components		Requirement	Capabilities
Center Plate	Temperature Rise @ 400W	$\leq$ 20 K	16.7 K
	Interface Heat Flux @ 400W	$\leq$ 25 W/in^2	17.6 W/in^2
85 K Cold Head	Safety Factor (Yield)	$\geq$1.5	4.4
	Safety Factor (Ultimate)	$\geq$2.5	5.9
	Margin of Safety (Q=90)	$\geq$0	1.55
	1st Mode	$\geq$250 Hz	770 Hz
35 K Cold Head	Safety Factor (Yield)	$\geq$1.5	2.8
	Safety Factor (Ultimate)	$\geq$2.5	3.2
	Margin of Safety (Q=90)	$\geq$0	0.27
	1st Mode	$\geq$250 Hz	511 Hz
H-Bar	1st Mode	$\geq$250 Hz	594 Hz

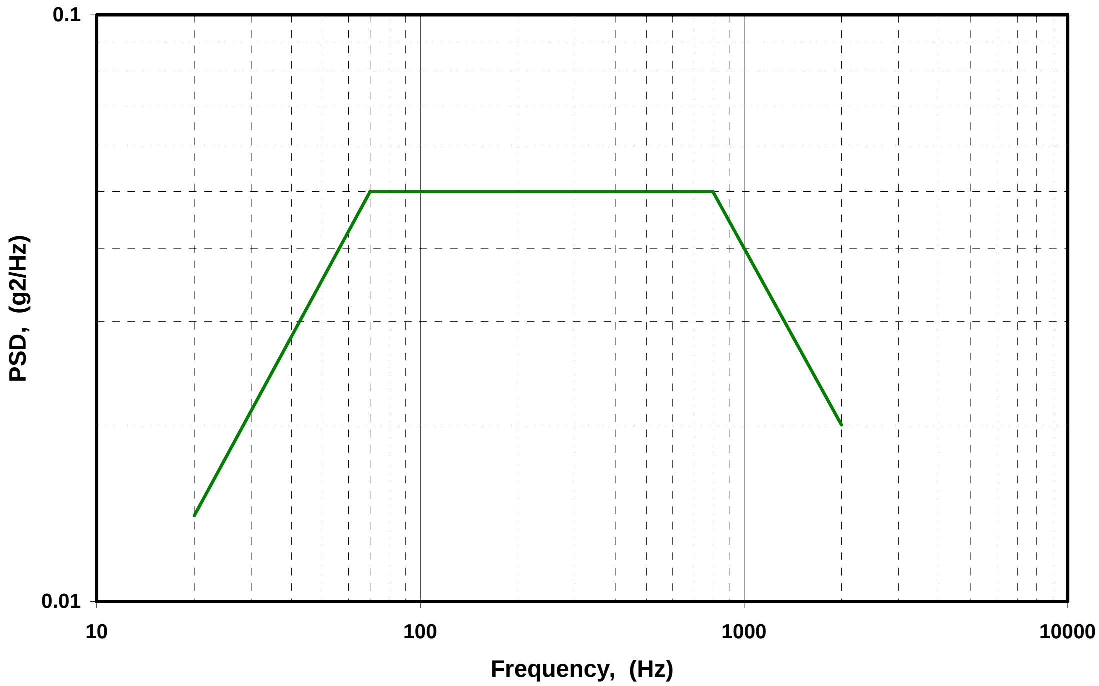

Figure 5. Random Vibration Profile

TABLE 4. Random Vibration Test Power Spectral Density

Frequency (Hz)	Reference Fig. 4.2	Acceptance (G^2/Hz)
20	G20	0.014
70-800	Ghigh	0.050
2000	G2000	0.020
Overall		8.65 Grms
Duration, per axis		1 minute

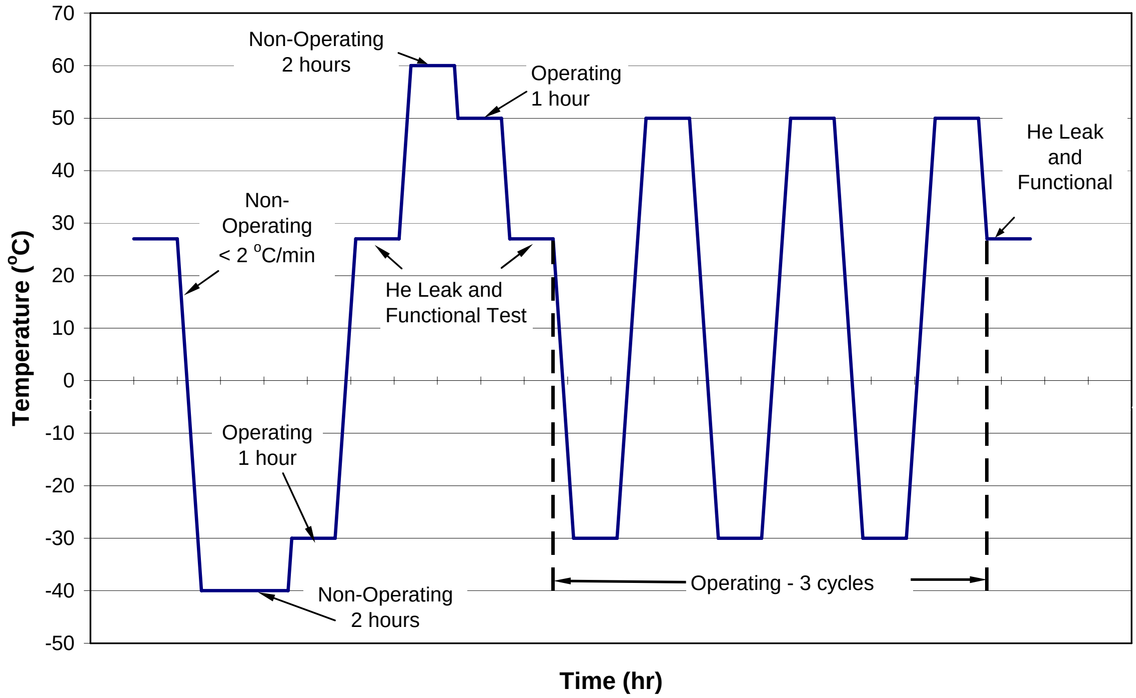

Figure 6a Thermal Cycle Test Profile

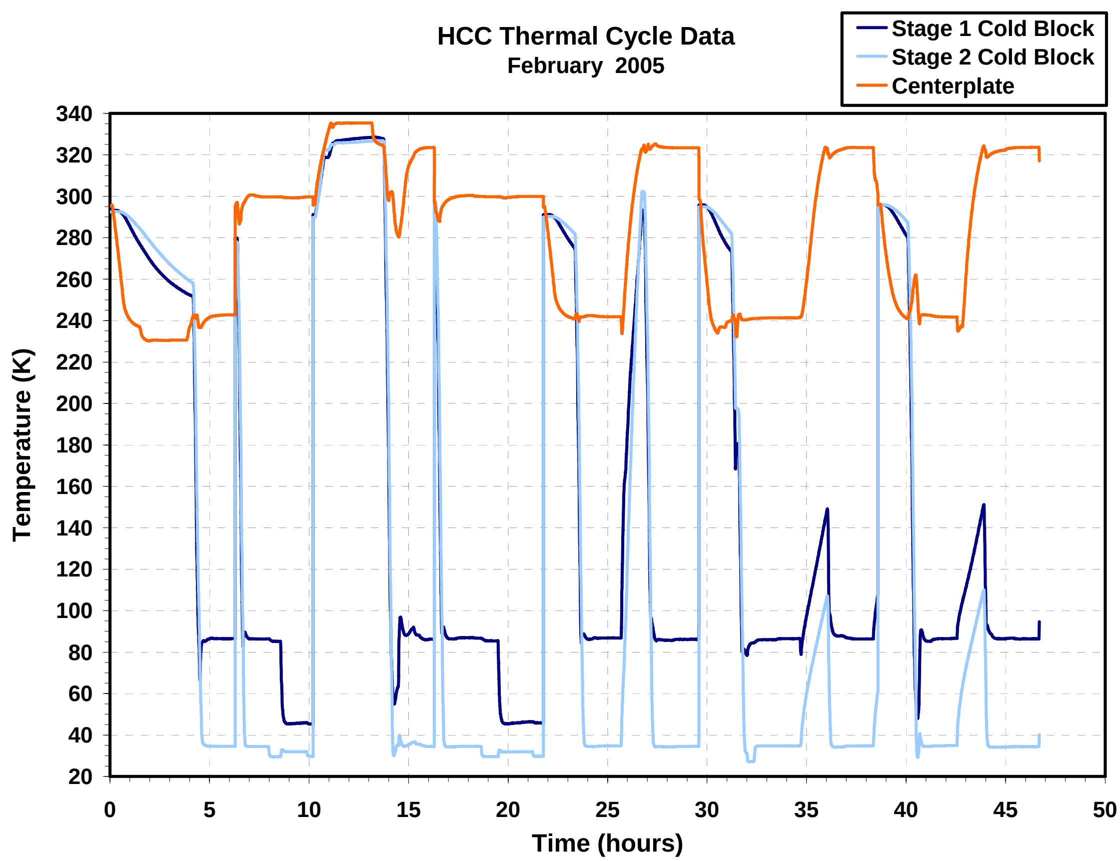

Figure 6b Thermal Cycle Test Data

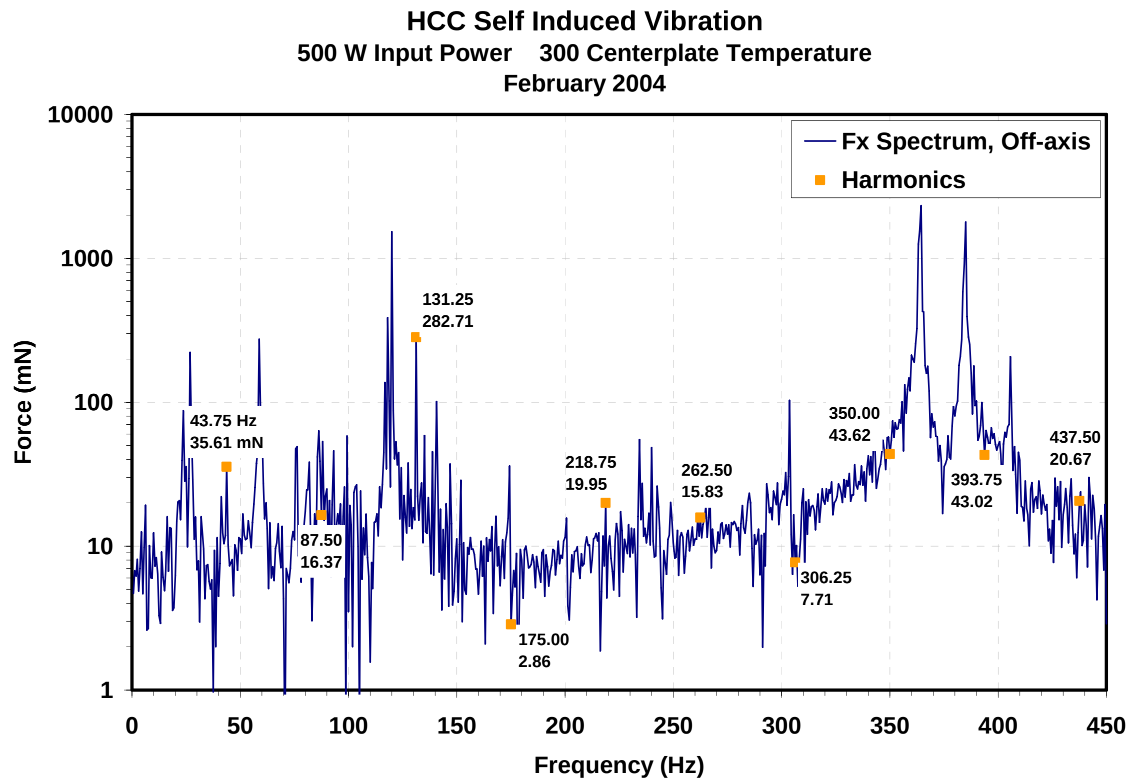

Figure 7 Self-induced Vibration: Off-axis Data

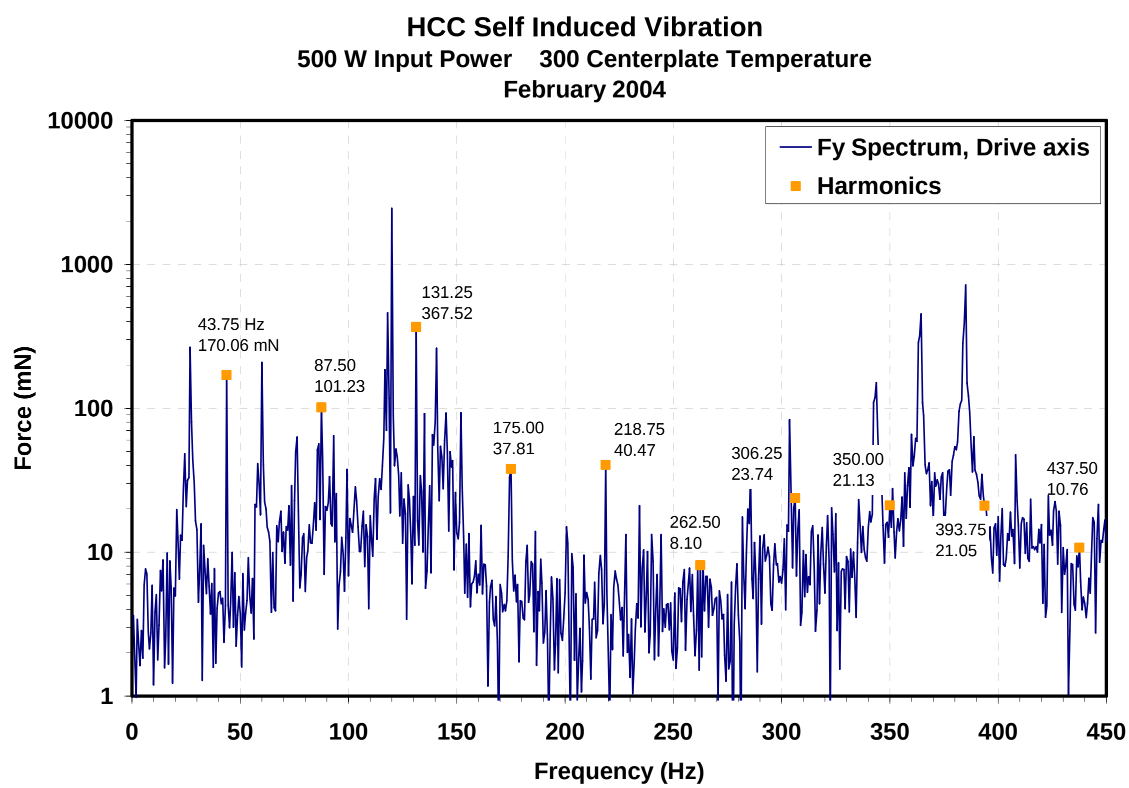

Figure 8 Self-induced Vibration: Drive-axis Data

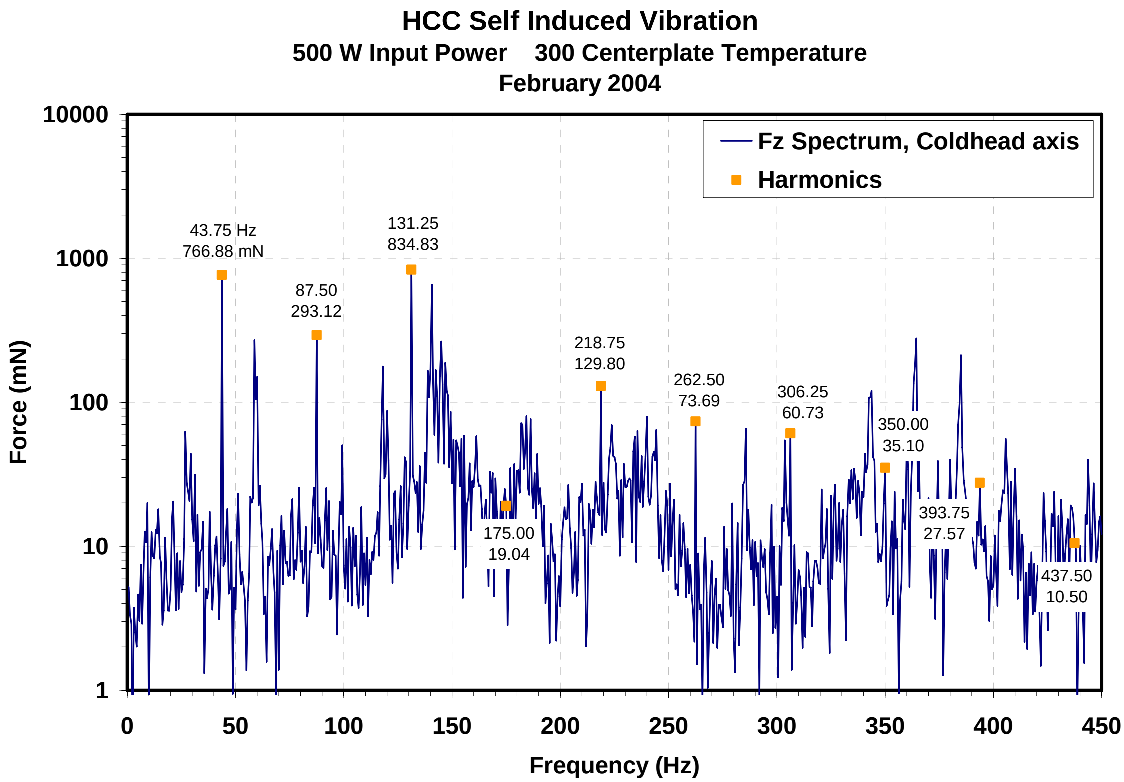

Figure 9 Self-induced Vibration: Coldhead-axis

ACKNOWLEDGEMENTS

This work was sponsored by the MDA. This work was performed for the Air Force Research Laboratory, Kirtland, NM, under contract number F29601-01-C-0226. The support of Thom Davis and Adam Smith is gratefully acknowledged.

REFERENCES

1. Tward, E., Chan, C. K., R., Colbert, Jaco, C., Nguyen, T., Orsini R., Raab, J., *Adv. In Cryogenic Engineering,* **Vol. 47B**, p. 1077 (2002).

2. Chan, C.K, Nguyen, T., and Jaco, C., "Two-stage pulse tube cooler" *Crycoolers 12,* edited by Ronald G. Ross Jr., Kluwer Academic/ Plenum Publishers, New York 2003, pp219-224.